FACET PWFA Program

Accelerator R&D HEPAP Subpanel

Mark Hogan, August 29, 2014

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

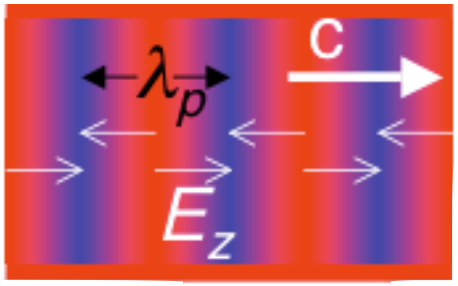
Why Plasmas?

Relativistic plasma wave (electrostatic):

$$\vec{\nabla}\cdot\vec{E}=\frac{\rho}{\varepsilon_0} \qquad k_p E_z=\frac{\omega_{pe}}{c}E_z=\frac{n_e e}{\varepsilon_0}$$

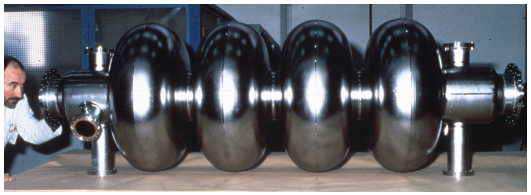
$$E_z=\left(\frac{m_e c^2}{\varepsilon_0}\right)^{1/2} n_e^{1/2}\cong 100\sqrt{n_e(cm^{-3})}=\underline{1GV/m}$$

$n_e=10^{14}$ cm^{-3}

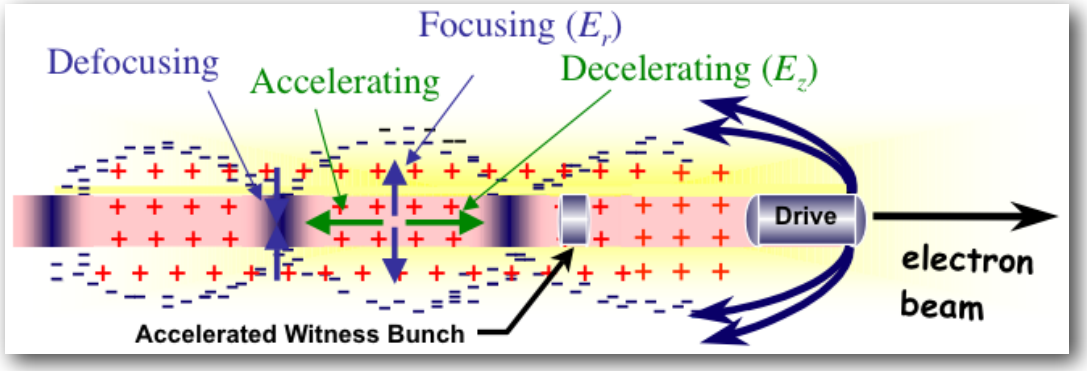


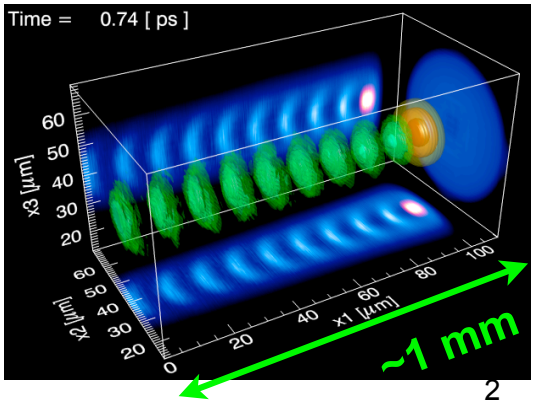
Large
Collective Response!

- Plasmas are already ionized, no break down
- Plasma wave can be driven by:
  - Intense laser pulse (LWFA)
  - Short particle bunch (PWFA)



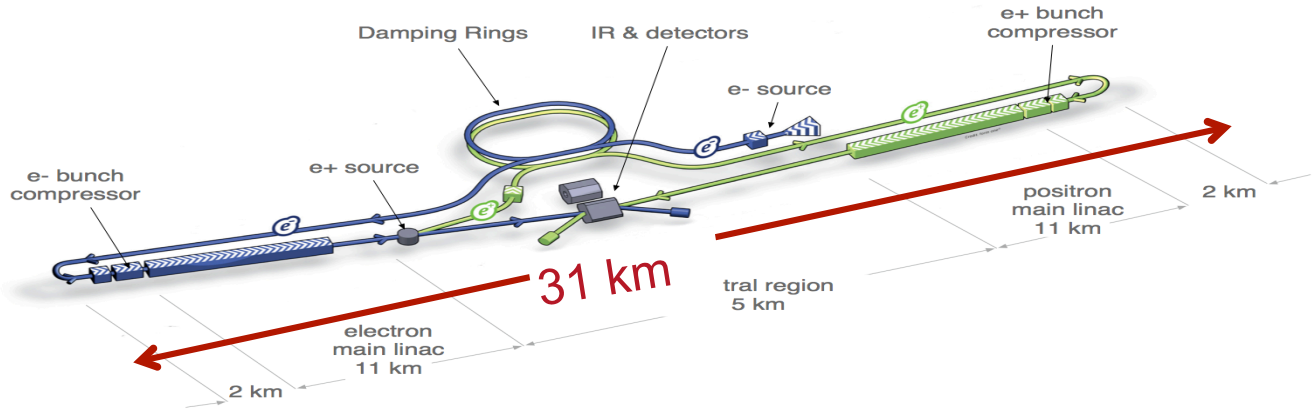
~1m



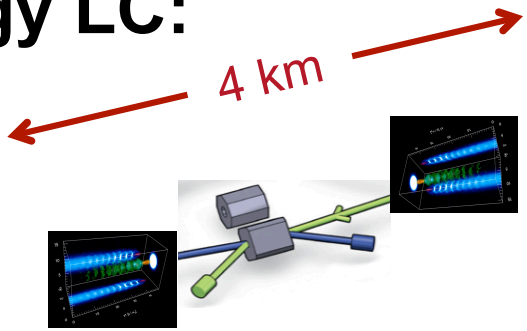


The Scale for a TeV Linear Collider

Today's technology LC – a 35km tunnel:



Plasma Wakefield Technology LC:

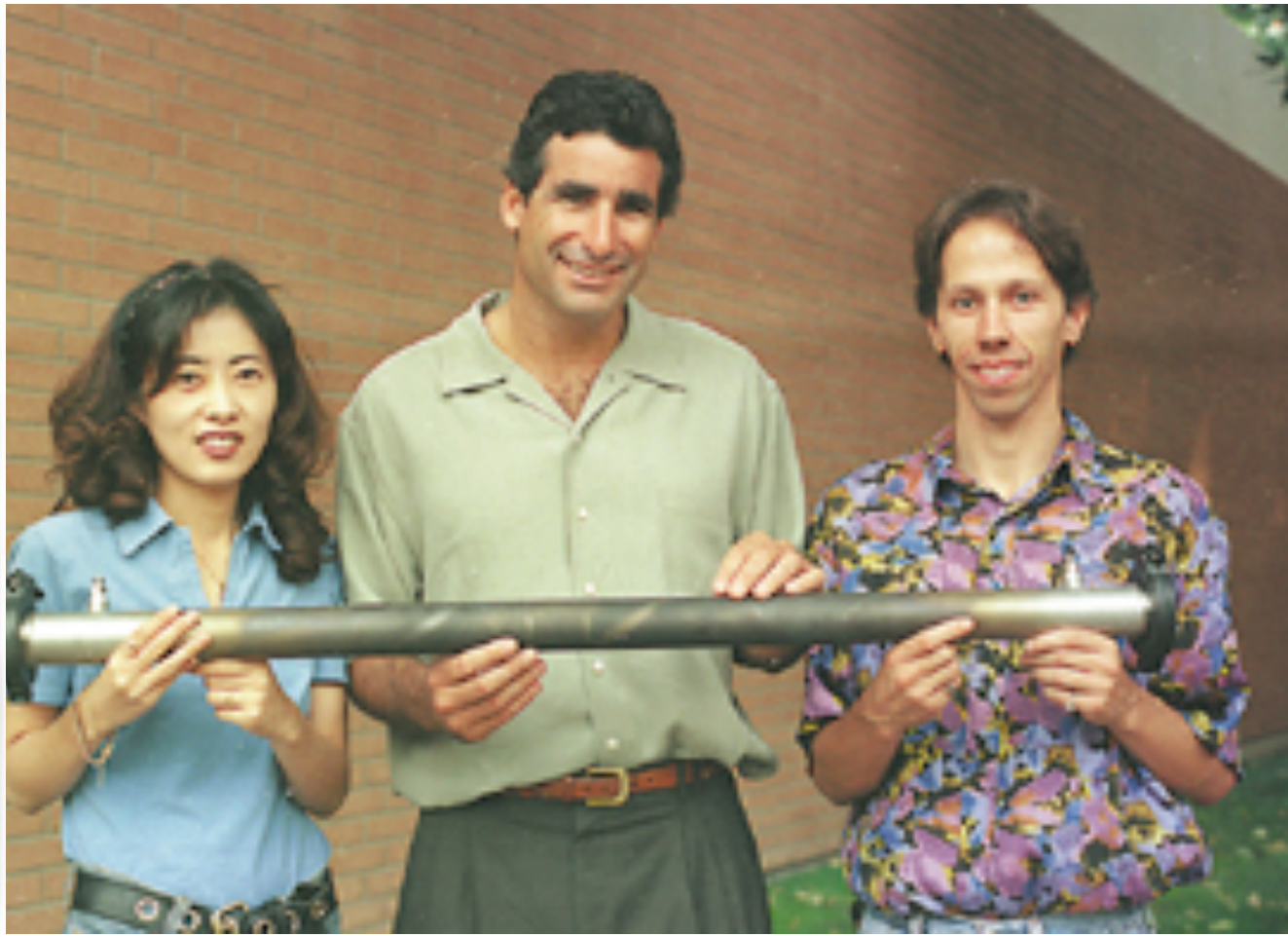


The Luminosity Challenge:

$$\mathcal{L} = \frac{P_b}{E_b}\left(\frac{N}{4\pi\sigma_x\sigma_y}\right)$$

Like Prof. Hansen on Stanford Campus Many Decades Before

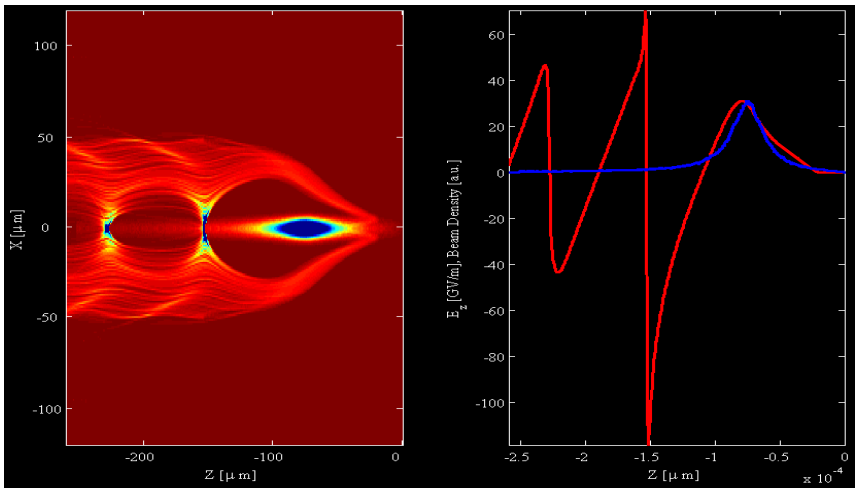
~4 MeV ——— 60 years ⟶ ~40 GeV



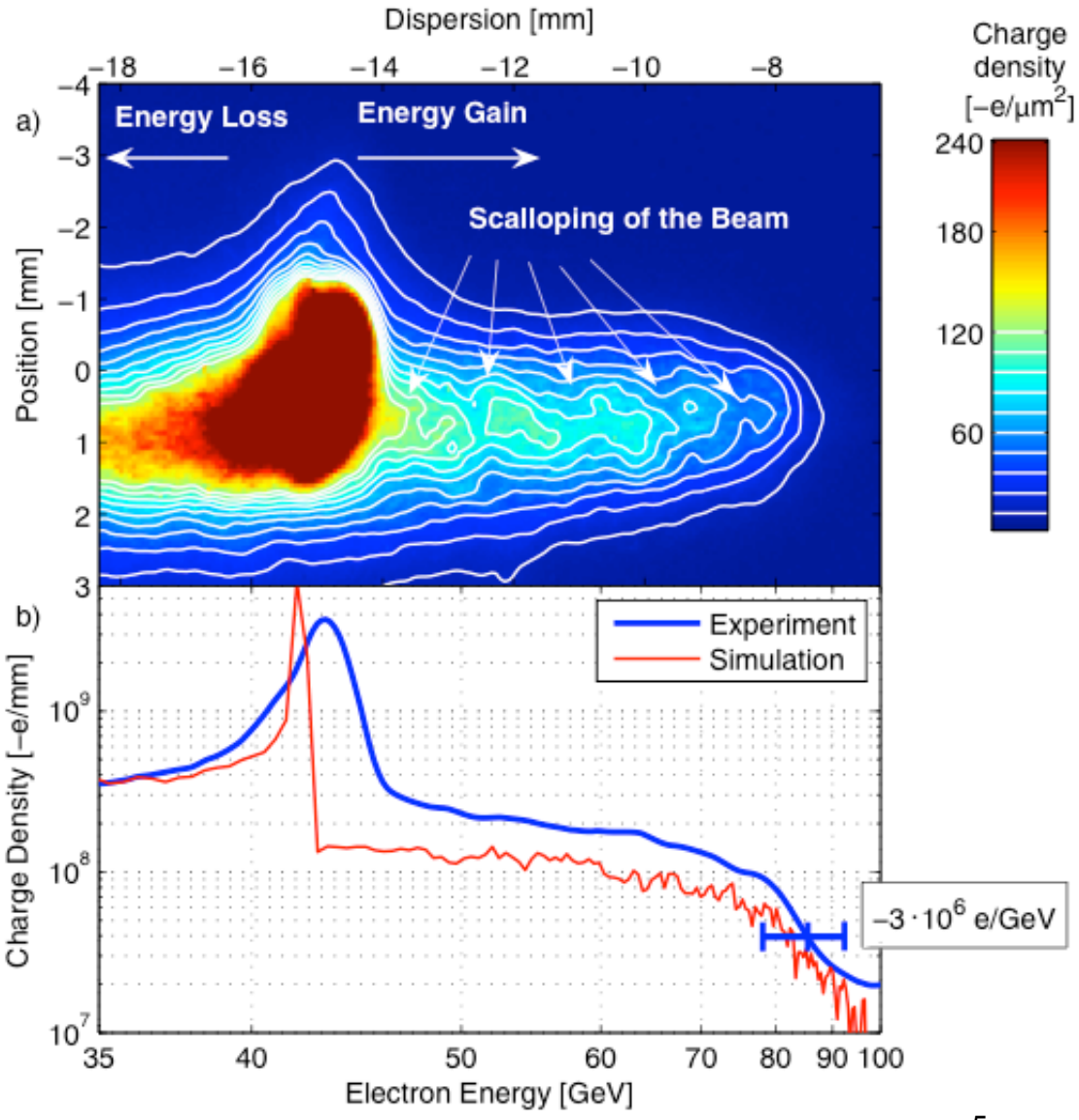
"We have accelerated electrons."

E-167: Energy Doubling with a Plasma Wakefield Accelerator in the FFTB

- Acceleration Gradients of ~50GeV/m (3,000 x SLAC)
  - Doubled energy of 45 GeV electrons in 1 meter plasma
- Single Bunch
- *Next Step:* Particle acceleration to beam acceleration @ FACET



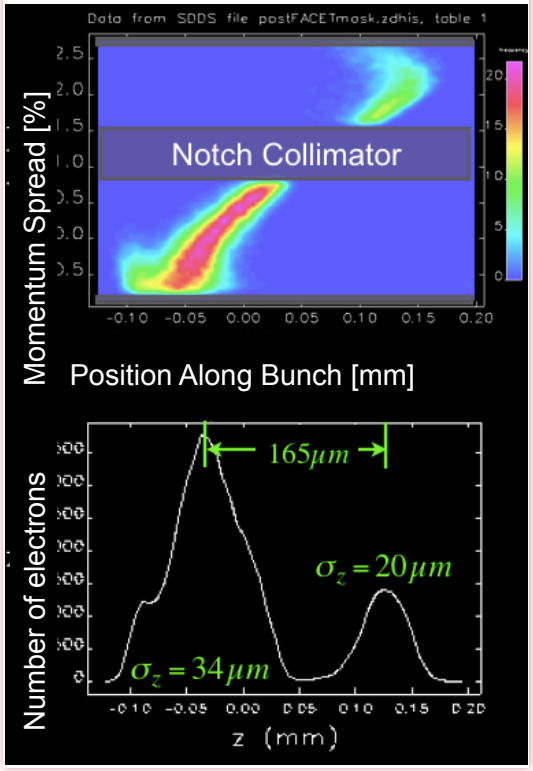
***Nature* 445 741 15-Feb-2007**



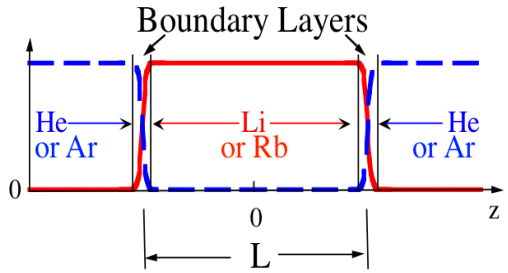
E200: Plasma Wakefield Acceleration @ FACET

UCLA SLAC

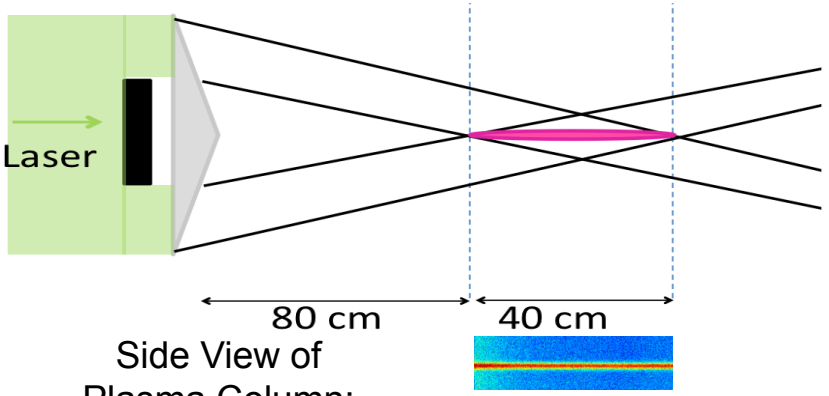
Simulation of Collimated Longitudinal Phase Space



Heat Pipe Oven for uniform column of low ionization potential vapor



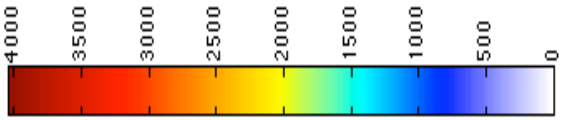
Line focus defines plasma channel aligned onto e⁻ beam orbit

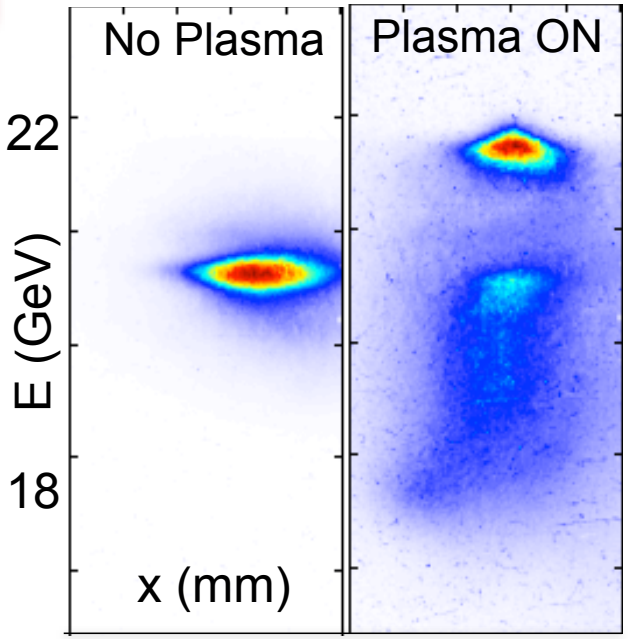


Side View of Plasma Column:

Accepted for publication in Nature (2014)

electron density (e^- mm^{-2})





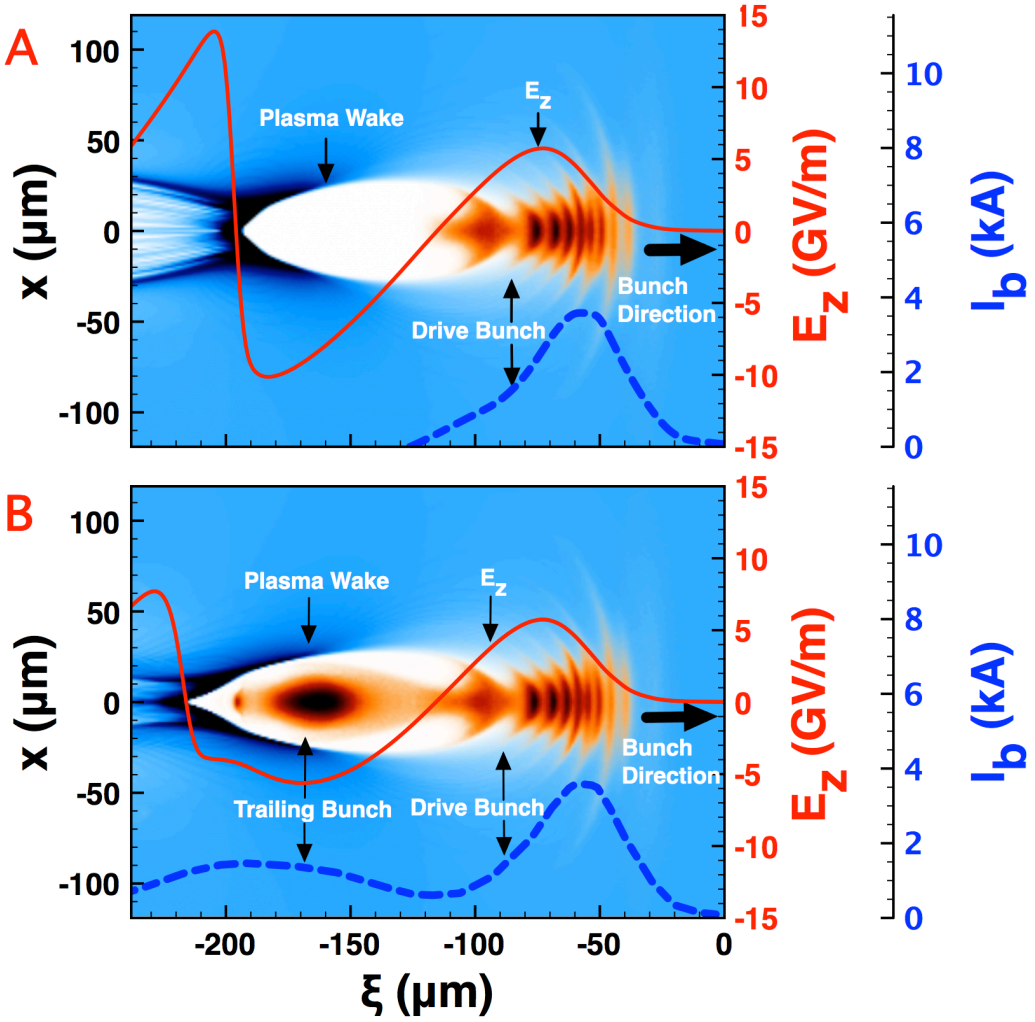
2 GeV Energy Gain
~2% dE/E

Up to 50% energy transfer from drive to witness was measured

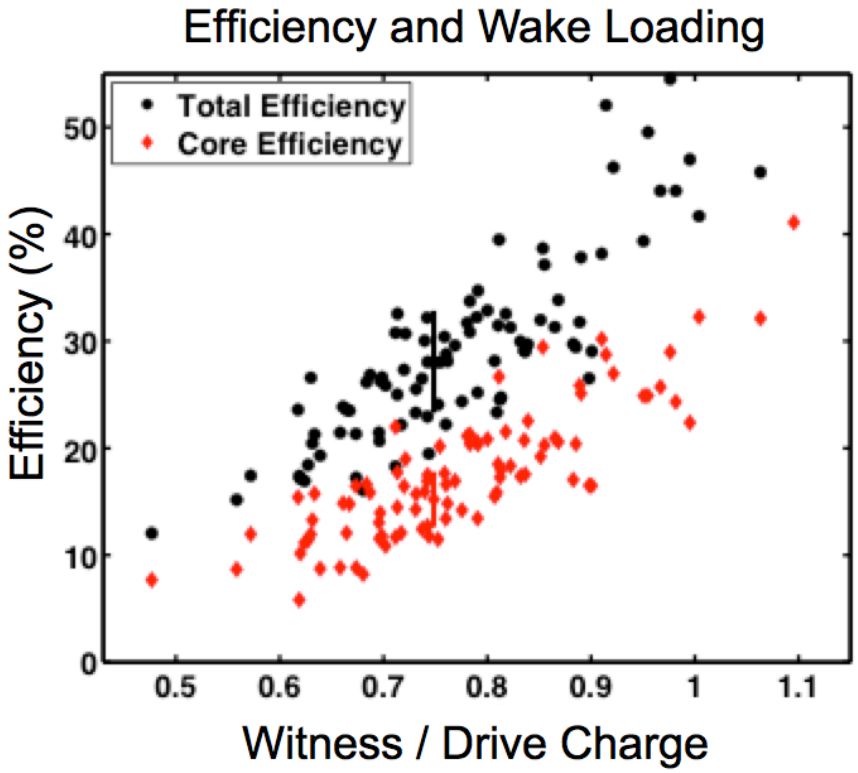
Efficiency correlates with loading of the wake

UCLA SLAC

QuickPIC Simulation



- More charge in witness beam loads accelerating wake more
- Energy spread anti-correlated

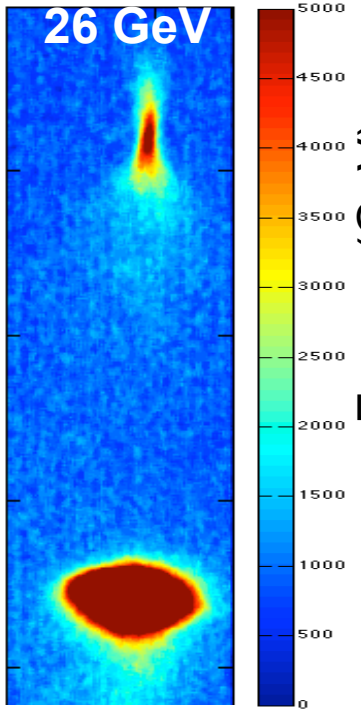


Beam loading is key to efficiency and narrow energy spread

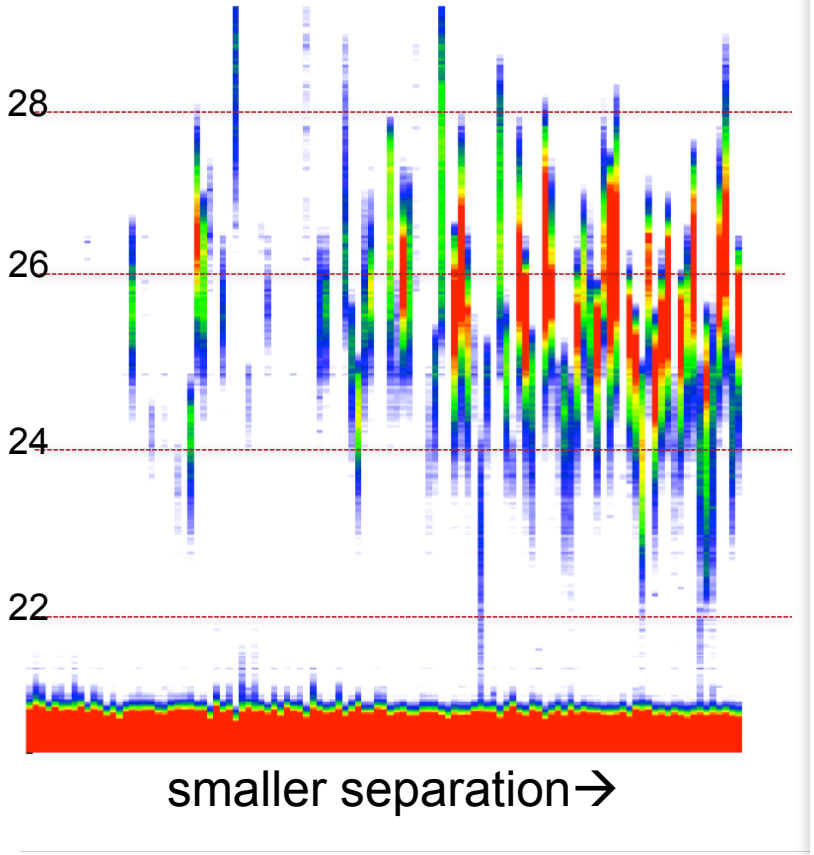
Increased Plasma Length → Increased Energy Gain

UCLA SLAC

Single shot with 6 GeV Energy Gain



100 Shots ordered by drive-witness bunch separation



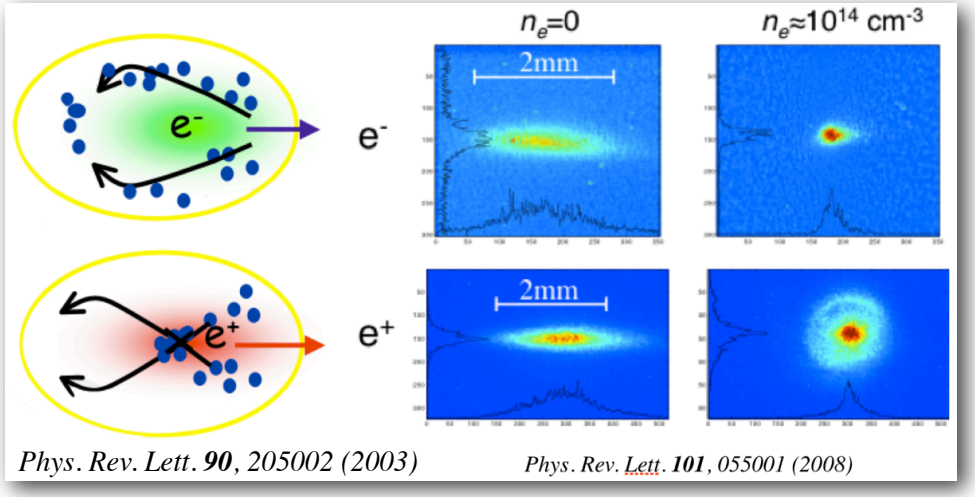
- High density = highest gradients but also tightest tolerances on loading, stability
- Develop tools & techniques to optimize accelerated beam at lower densities first
- Early analysis:
  - ~100pC accelerated
  - O(10%) energy spread
  - Mean energy gain 6 GeV

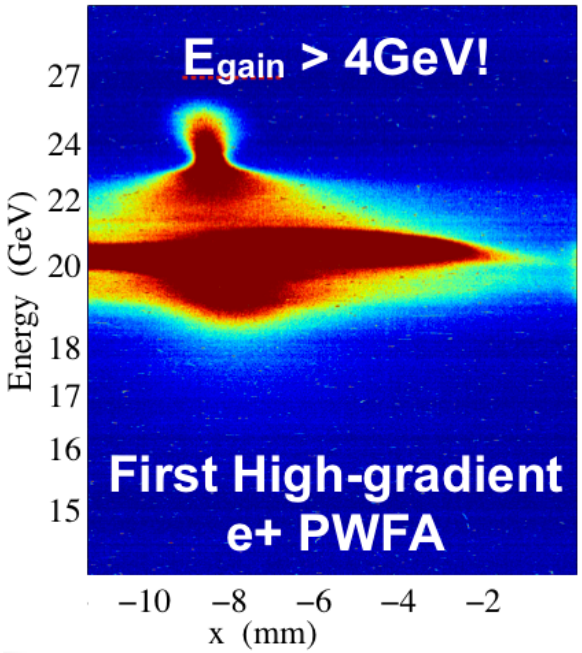
Good agreement between observed and expected energy gain in a longer plasma for several plasma densities

E200: Commissioned Compressed Positrons This Run!

UCLA SLAC

- Focusing and acceleration of positrons has been characterized at low densities at SLAC FFTB
- With high-density, nonlinear wakes there is narrow region that accelerates and focusses positrons





- Expected e+ beam to tear itself apart in high-density plasma
- **Results are more forgiving – source of active discussions / simulations!**

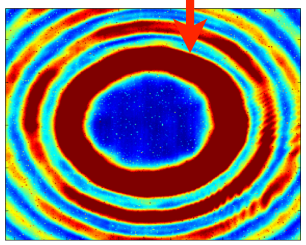
FACET Has the Only Active Plasma Acceleration Program with Positrons in the World

T504: Positrons and Hollow Channel Plasmas

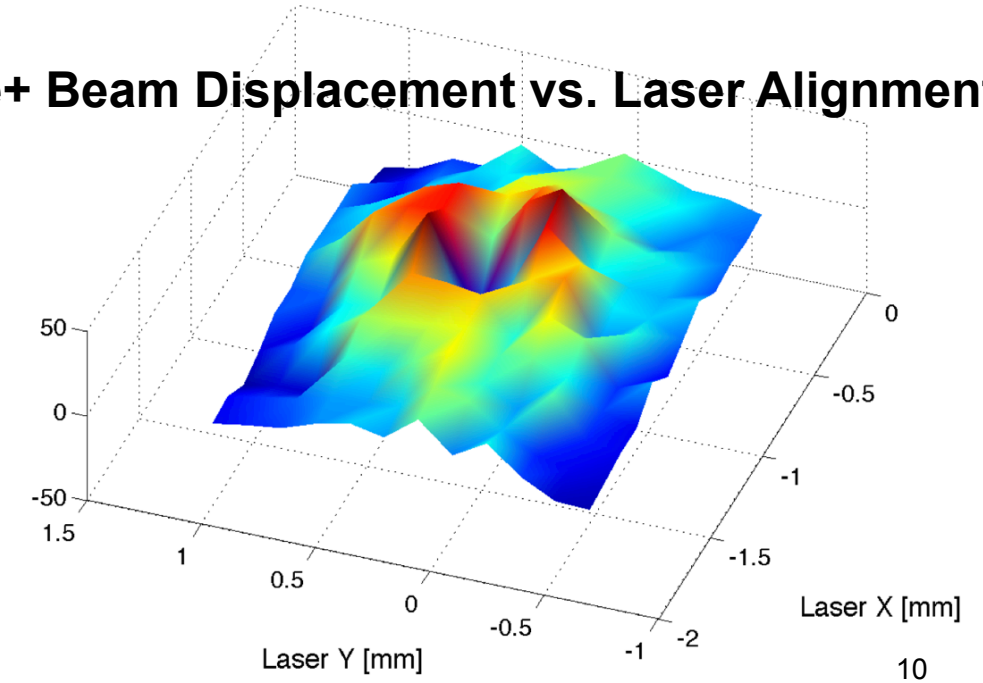
UCLA SLAC

- Hollow channel plasmas might be a viable method for accelerating positrons in a plasma
- A special optic called a kinoform is used to create a hollow channel plasma
- Have experimentally created a hollow channel plasma and tested it with a positron beam

Hollow Channel (400μm ID)



e+ Beam Displacement vs. Laser Alignment



First tests verified we can create and align the hollow channel to the positron beam

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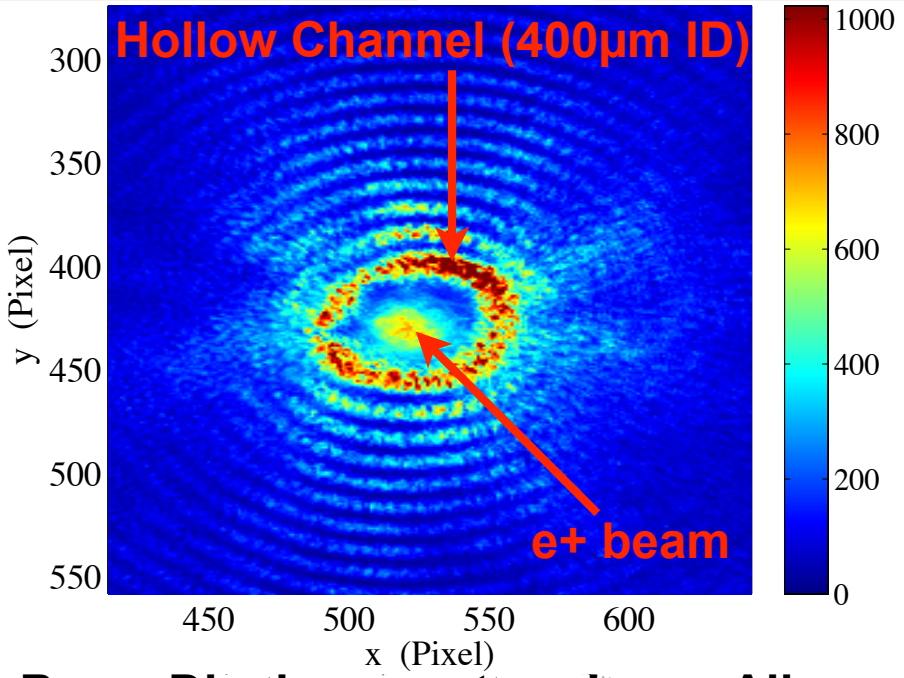

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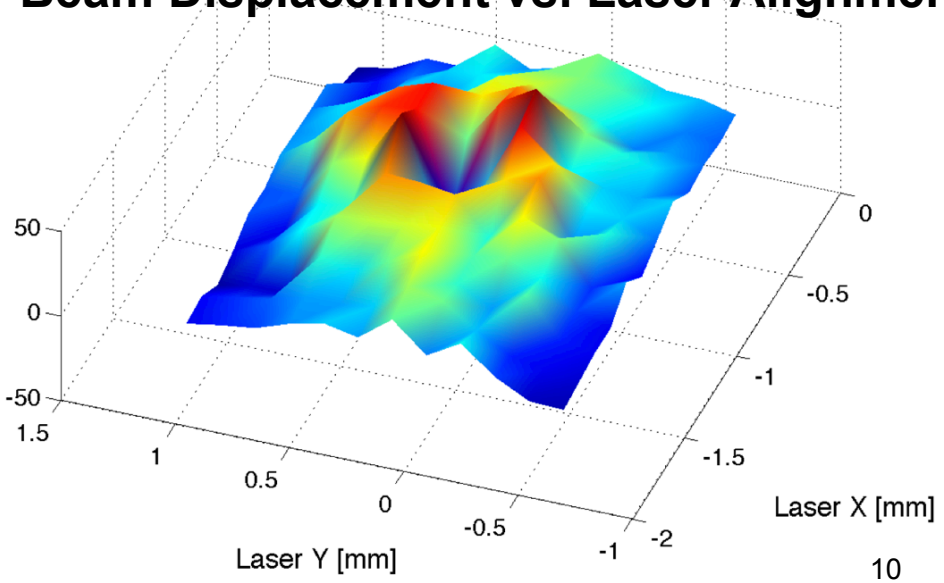

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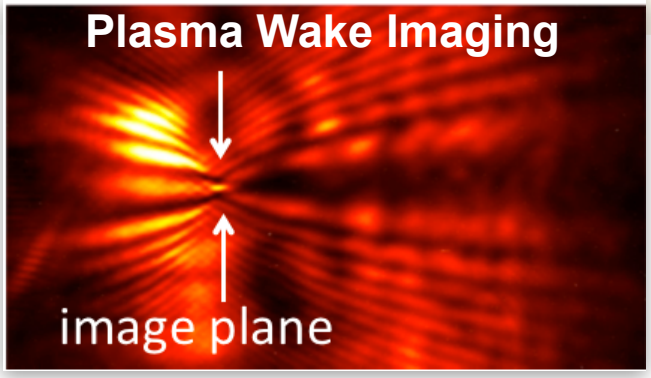
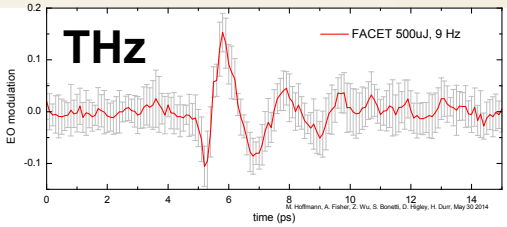
PWFA Program Plan as Shown December 2012

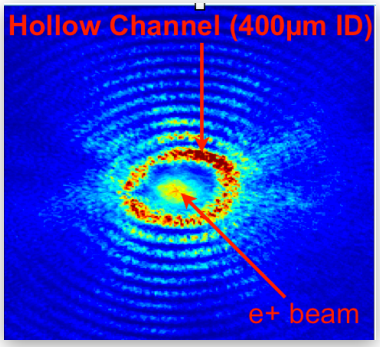
FY	Facet Run	LCLS off	PWFA goal
2013	2/1 - 6/30	8/6 - 9/30	2 beam generation, laser commissioning, **2 beams with laser->** mono energetic acceleration **(all successful and more…)**
2014	10/15-12/20 2/1 - 6/30	8/1 -10/30	2 beams with laser-> **mono energetic acceleration**, positron commissioning, positron PWFA, high brightness PWFA injector **(all successful)**
2015	10/7 - 12/20	8/1 - 9/30	**positron PWFA**, one stage, efficiency, high brightness PWFA injector
2016	10/1-3/31	4/1 S0-10 D&D	Finalizing the program, **single stage demonstration** (energy spread, emittance, efficiency)

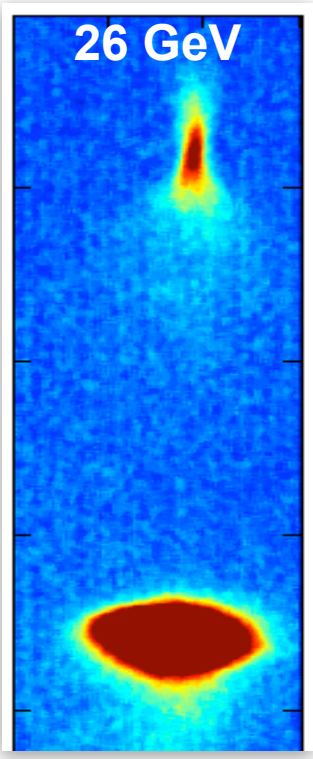
Steady, methodical progress according to our plan

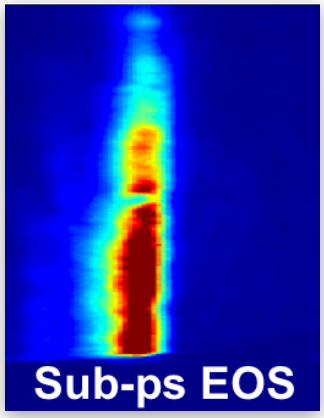
FY14 Run: FACET manages a focused program on PWFA and a variety of user experiments...both benefit

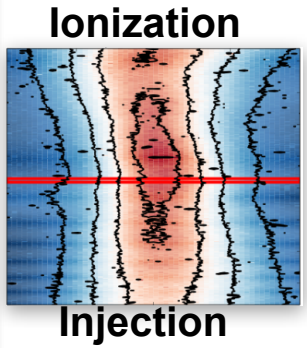


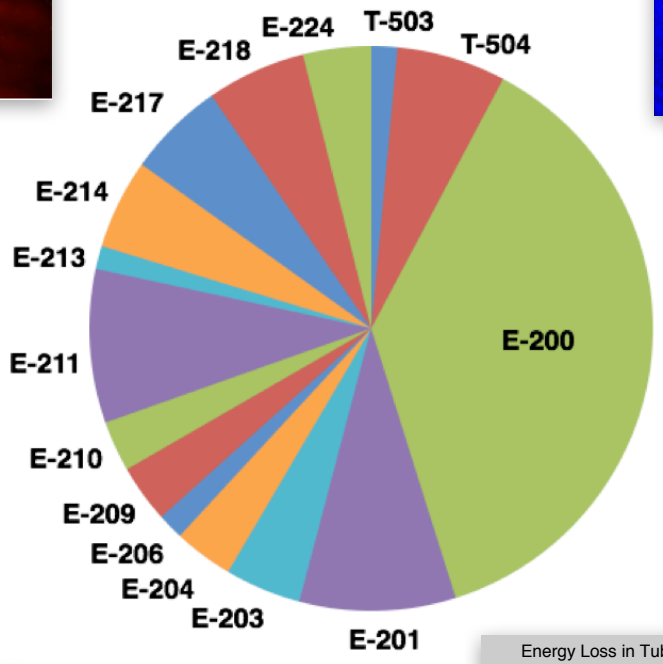


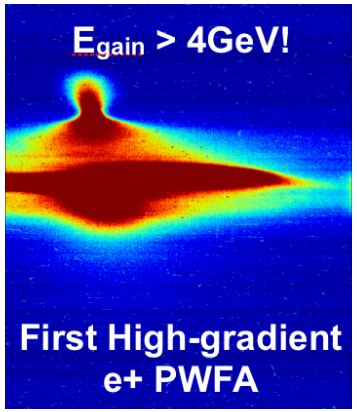


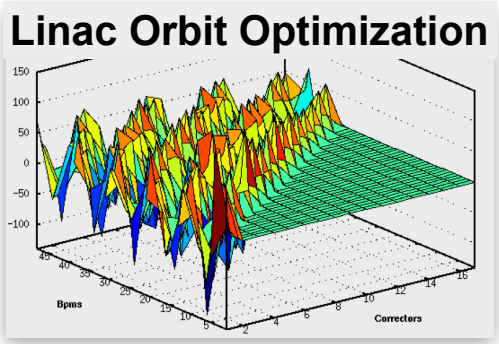


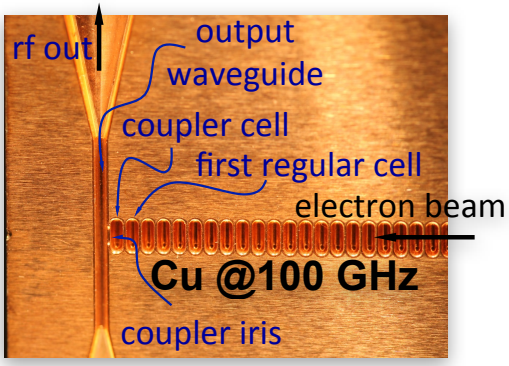


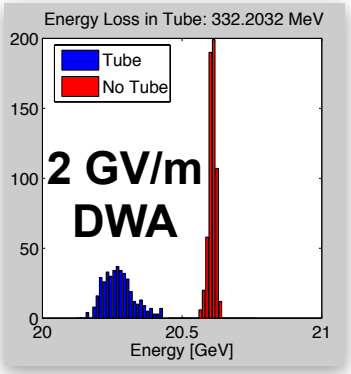


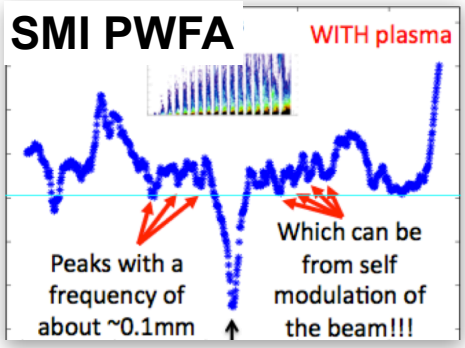






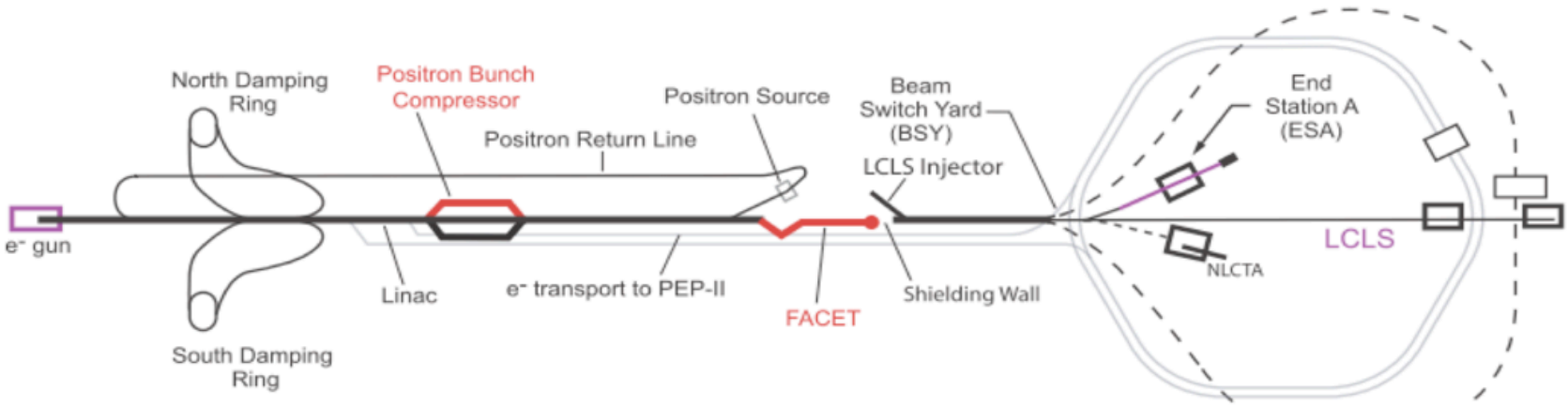




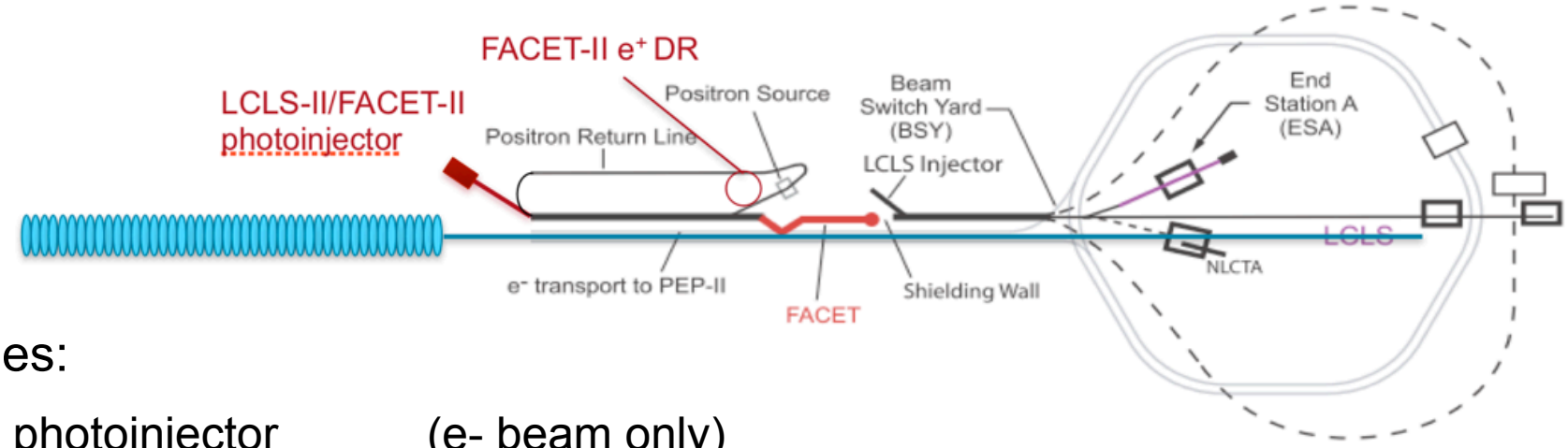


From FACET to FACET-II

FACET Today



FACET-II



Three main stages:

- Electron beam photoinjector (e- beam only)
- Positron damping ring (e+ or e- beams)
- "Sailboat" chicane (e+ and e- beams)

FACET-II plan will use 2nd 1/3 of the tunnel

PWFA Goals for FACET-II

FY	FACET-II	PWFA Goals
2017	Construction (Phase 1)	Finalize FACET data analysis, prepare FACET-II experiments
2018-19	Phase 1 (e^- only)	**Staging studies** with witness injector (synchronization, alignment), high transformer ratio (with shaped bunches)
2020-21	Phase 2 (e^- or e^+)	e^- or e^+ acceleration in e^+ wakes (physics of p driven PWFA), **high-brightness beam** generation, preservation, characterization
2022-23	Phase 3 (e^- and e^+)	**e^+ acceleration** in e^- driven wakes, demonstration of e^+ acceleration stage
2024-25		Witness bunch acceleration in **two PWFA stages** (independently driven)

Staging Will Be Required to Reach Very High Energies

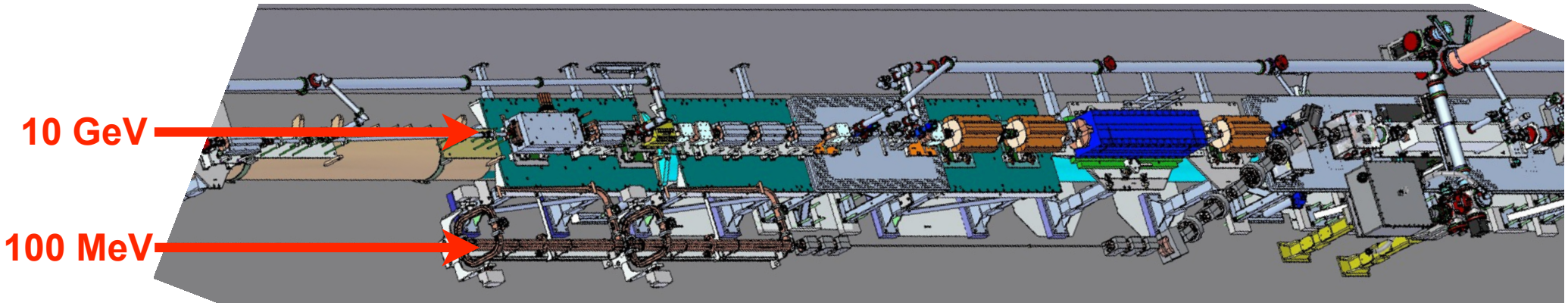
SLAC

Upstream of stage:

- Inject high-brightness witness bunch from independent source
- Can adjust/tailor individual current profiles
- Investigate tolerances on timing, alignment

Downstream of stage:

- Extract/Dump spent drive beam
- Preserve emittance of accelerated beam



FACET-II has all the tools to investigate staging multiple plasma cells together as desired for very high energy applications

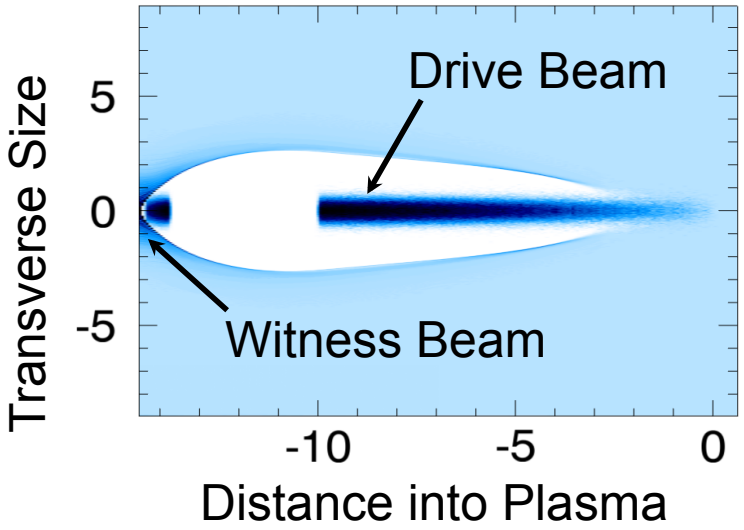
Shaped Current Profiles Maximizes Efficiency, Energy Gain

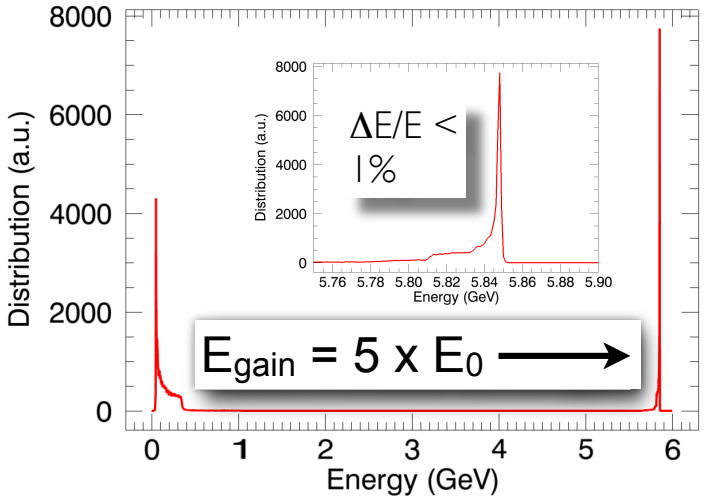
Shaped drive bunch:

- High transformer ratio = larger energy gain per stage
- Most efficient energy extraction

Independently shaped witness bunch:

- Emittance preservation at μm level
- Optimal beam loading for low energy spread, maximum efficiency



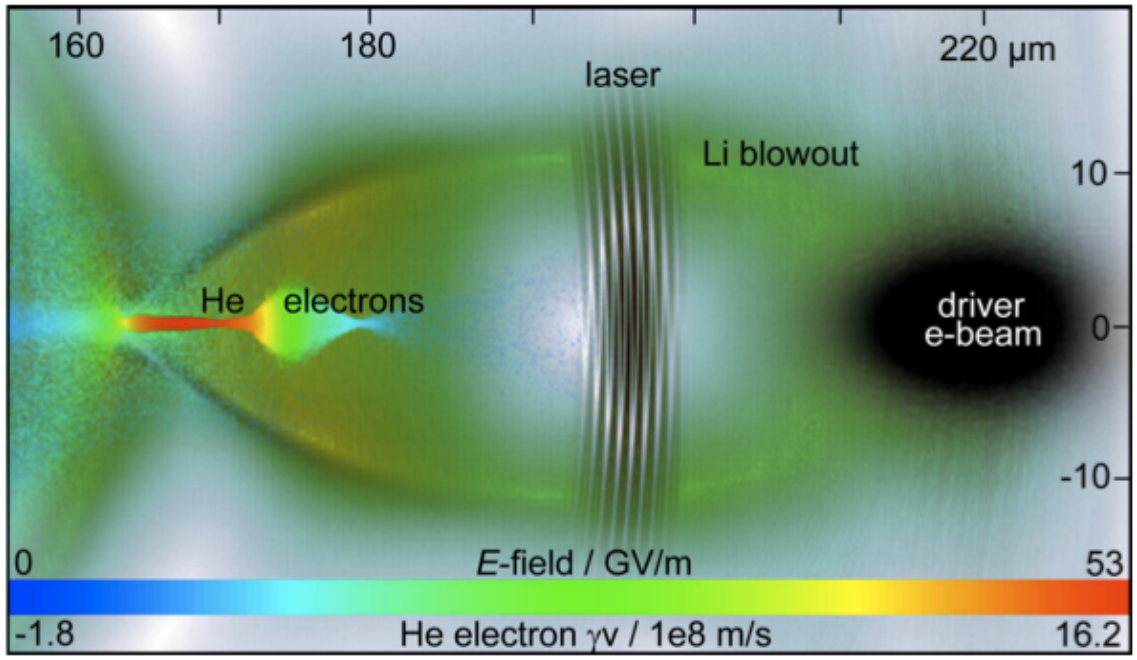


Experiments will optimize performance of single stage electron acceleration

Creating Ultra High-Brightness Beams with PWFA

- Plasma bubble (wake) can act as a high-frequency, high-field, high-brightness electron source
- Photoinjector + 100GeV/m fields in the plasma =
  - Unprecedented emittance (down to 10^{-8} m rad)
  - Sub-μm spot size
  - fs pulses

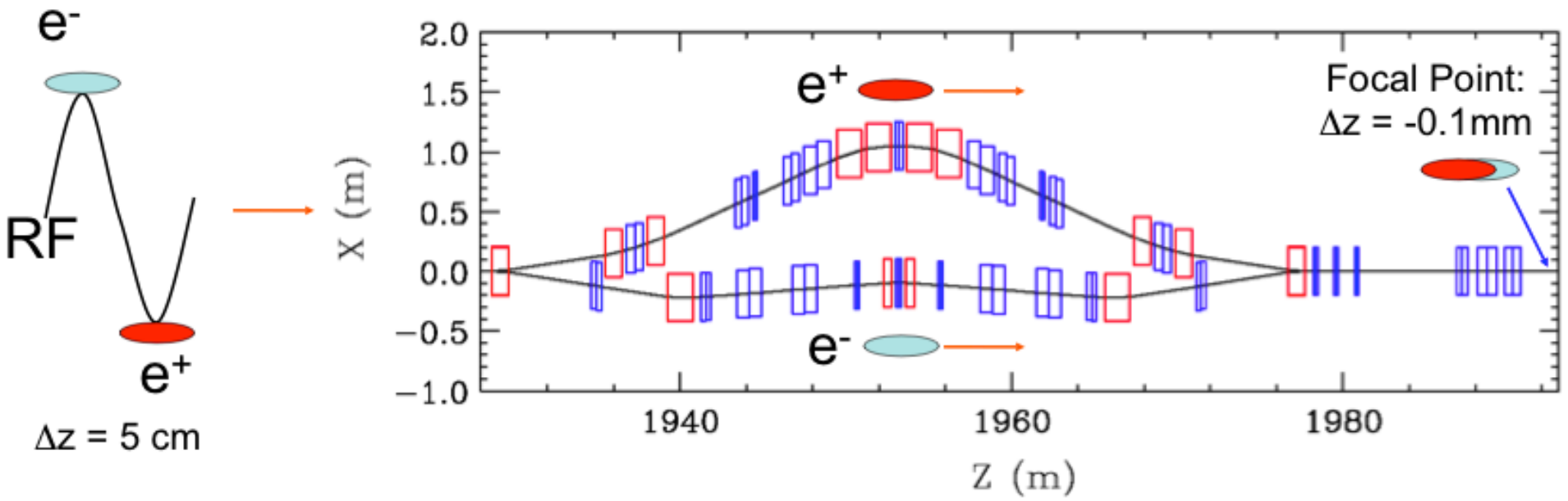
'Trojan Horse Technique'



Generate beams with unprecedented brightness for tests of nm emittance preservation and first applications

Sailboat Chicane in FACET-II

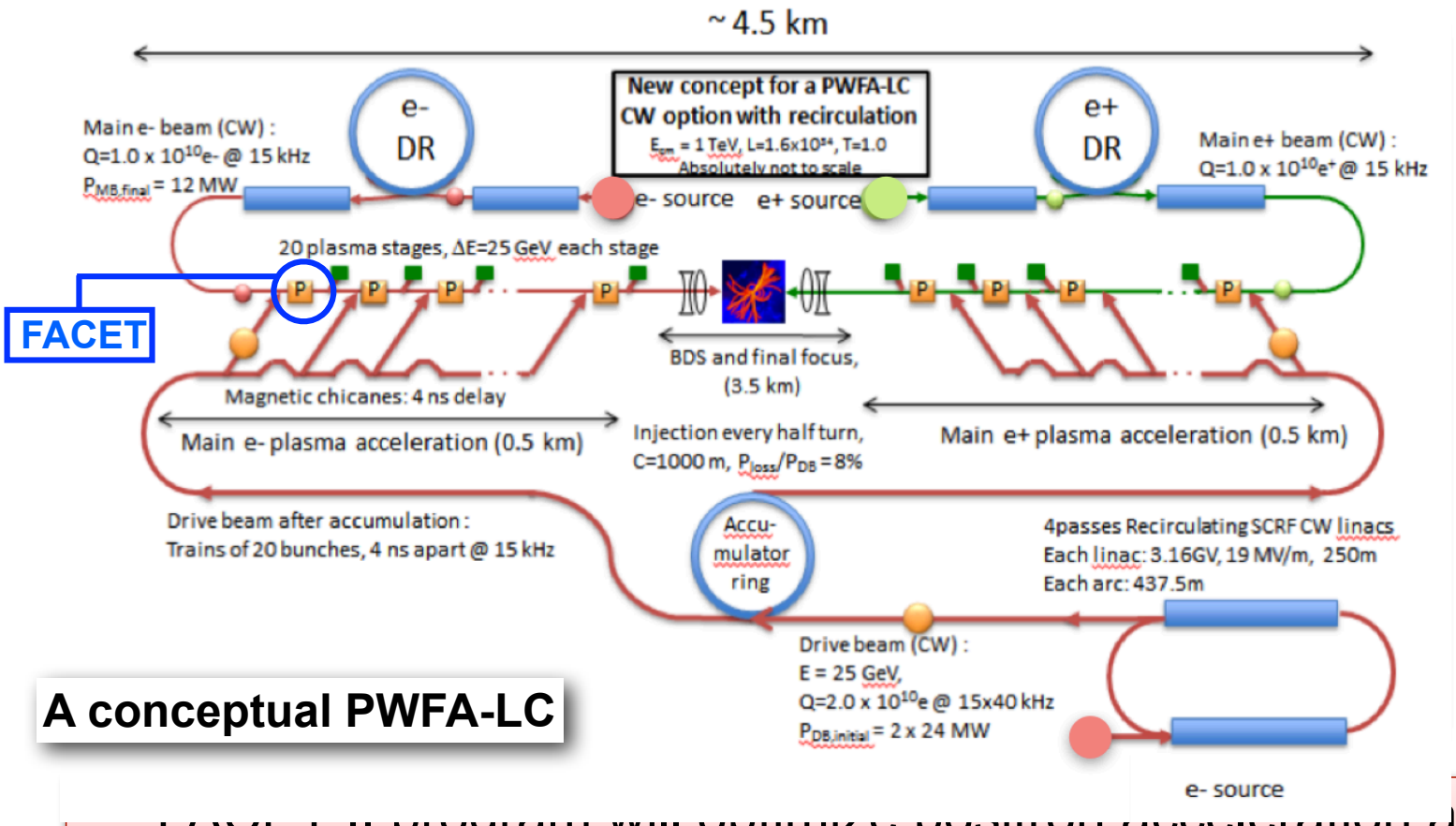
- Phase 3 adds second (top) half to existing beamline in S20
- Use 'Sailboat Chicane' to adjust delay of e^- and e^+ at plasma entrance
- Large beam loading of e^- wakes with high charge e^+ beams



Opens up many new avenues of research: Positron acceleration on electron driven wakes, PD-PWFA, Fast magnetic switching…

FACET in the Middle of the 2nd Phase of PWFA

- SLAC FFTB demonstrated electron acceleration with 50GeV/m for 85cm
- FACET addresses issues of a single stage
- FACET-II staging, high-brightness beams



A conceptual PWFA-LC

E_{cm} = 1 TeV
L = 10^{34} cm^{2}s^{-1}
Efficiency$_{wall\ plug}$ ~ 11%

SLAC-PUB-15426
http://arxiv.org/abs/1308.1145
E. Adli *et al*, IPAC14

FACET-II program will optimize positron acceleration and investigate issues of staging multiple plasma cells for very high energy

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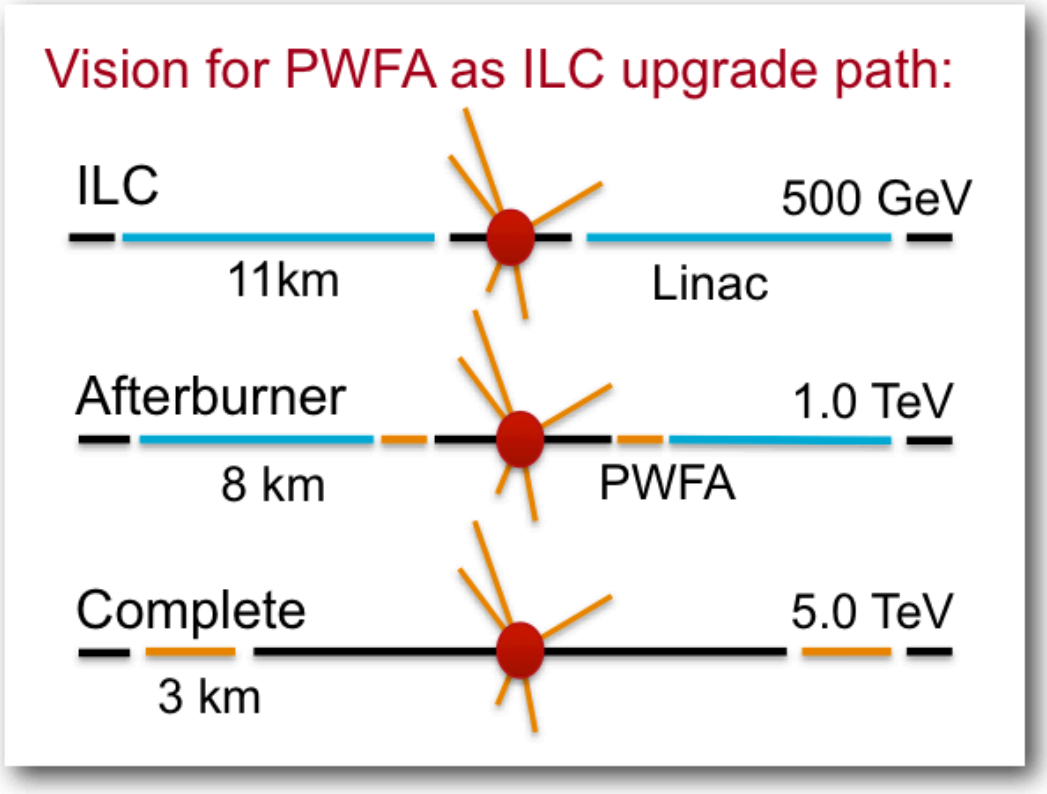


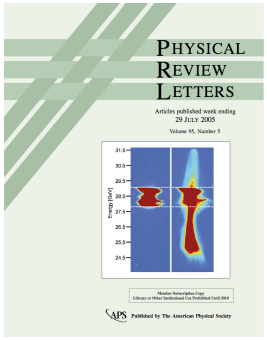
FACET-II program will optimize positron acceleration and investigate issues of staging multiple plasma cells for very high energy

Summary

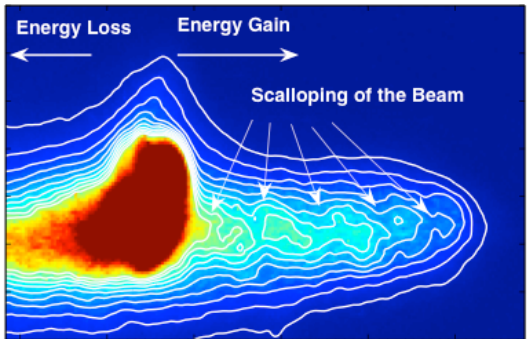
Plasma wakefield acceleration presents an enormous opportunity!

- Success follows naturally from mixture of compelling scientific questions, strong collaborations and powerful test facilities
- SLAC linac continues to play an invaluable role: FFTB, FACET, FACET-II

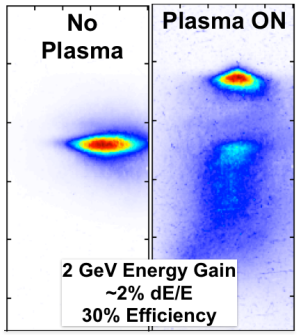
Accelerating Gradient

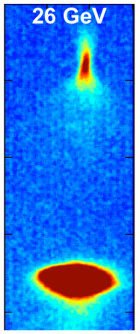


High Energy

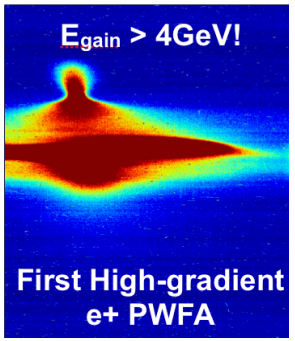


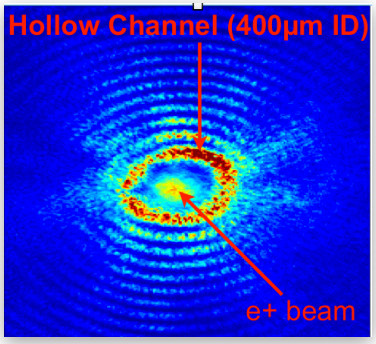
Beams, Efficiency





Positrons





"People who say it cannot be done should not interrupt those who are doing it" – George Bernard Shaw